Plasma-enhanced Inverse Compton Scattering Production of Polarized Positrons

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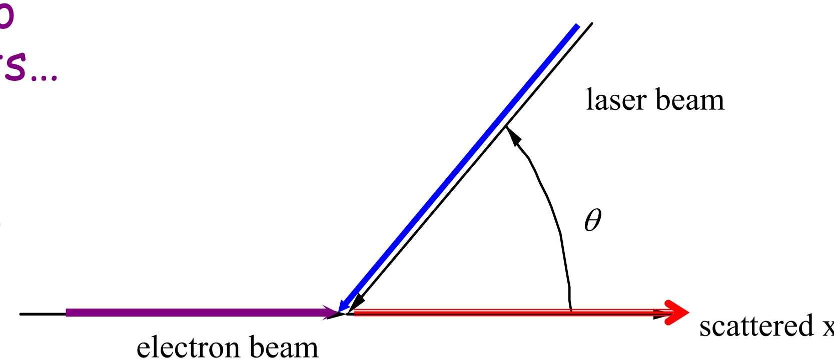
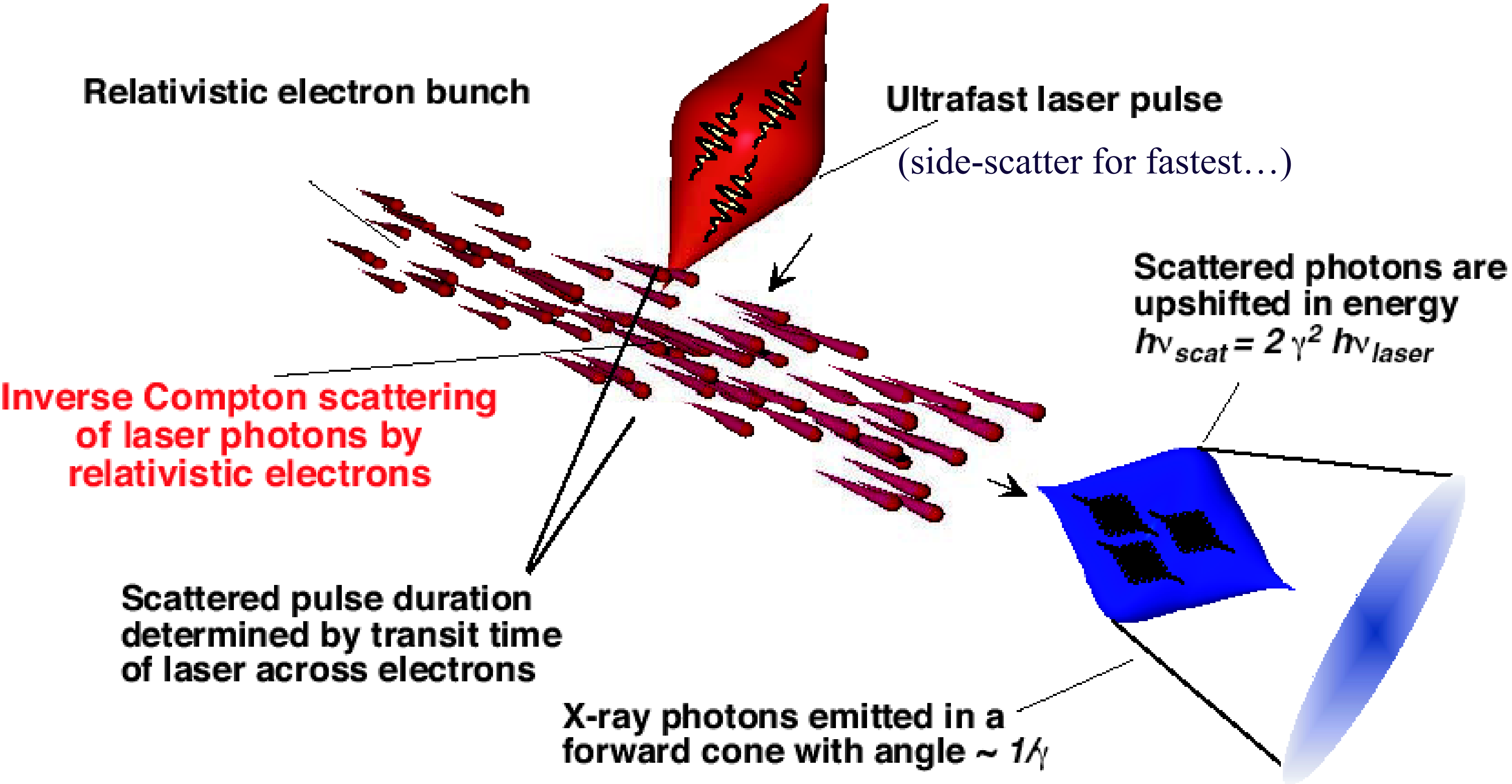
Introduction

- Inverse Compton scattering provides a path to 4th generation x-ray source and other delights…
- Doppler upshifting of intense laser sources; “monochromatic” source
- Very intense electron and laser beams needed
- Extremely diverse uses
  - High energy density physics (shocks, etc.)
  - Medicine
    - Diagnostics (dichromatic coronary angiography)
    - Enhanced dose therapy
  - High energy physics
    - Polarized positron sourcery
    - Gamma-gamma colliders
- What can we learn from present efforts?
  - Beam focusing?
  - Bunching?

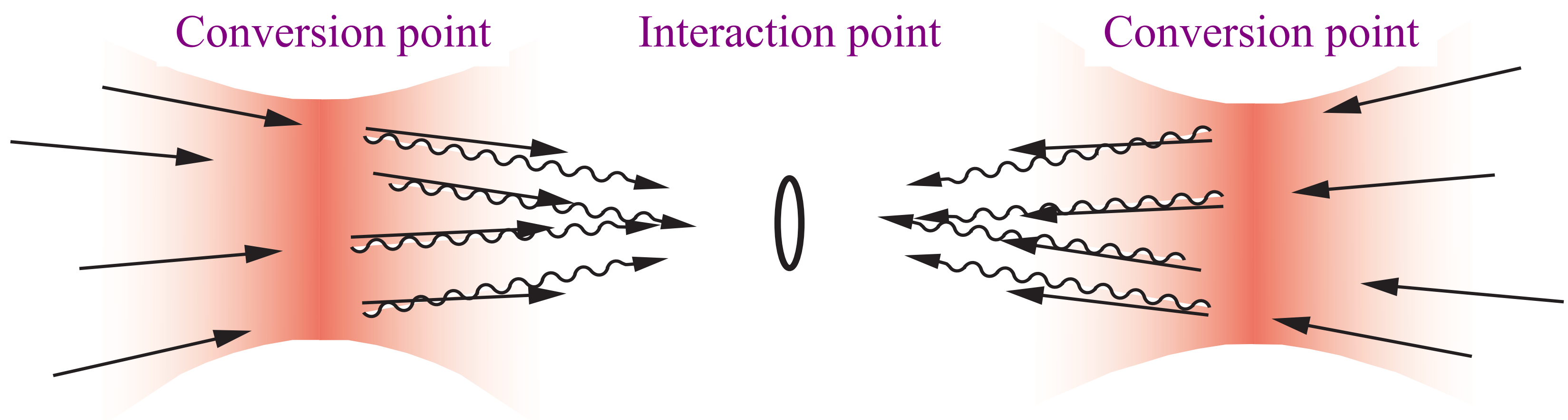


$$\lambda_\gamma \cong \lambda_L / 2(1+\cos(\theta))\gamma^2$$

Inverse Compton process

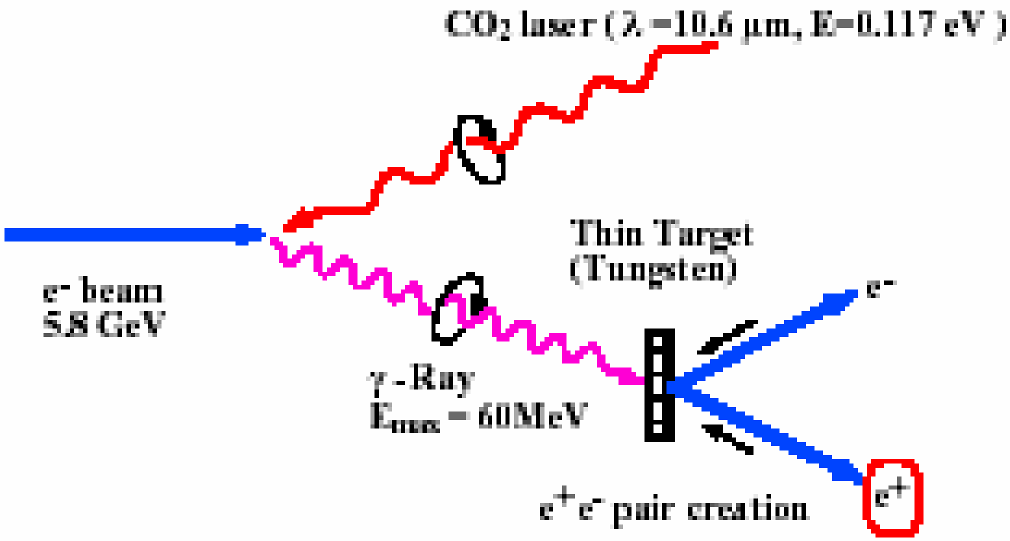


HEP 1: Gamma-Gamma collisions



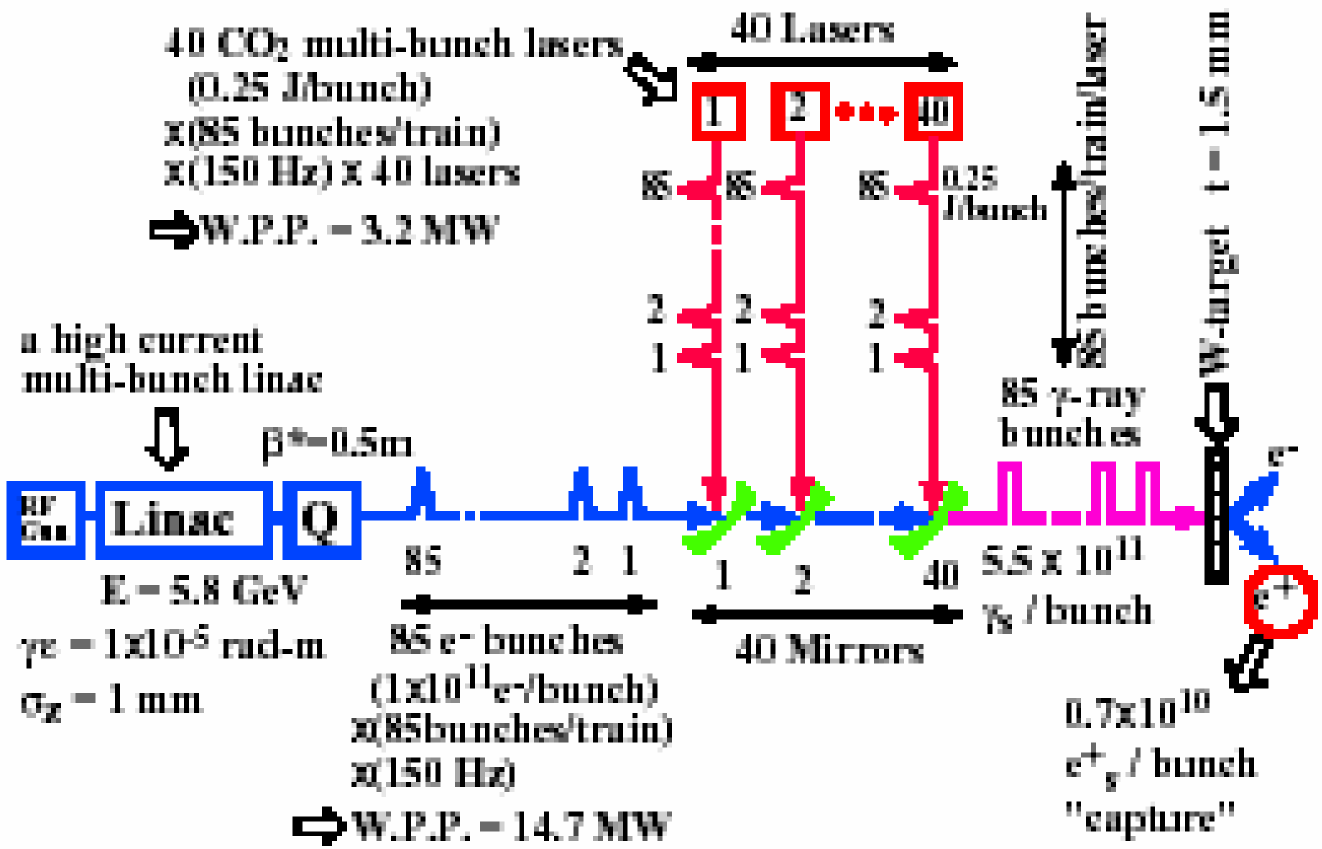
- Start with an electron linear collider
- Collide the electron bunches with a laser pulse just before the IP to produce high energy photons (100's GeV)
- Requires:
  - Lasers
    - Pulses of 1J / 1ps @ 11,000 pulses / second (with beam format!)
  - Optics
    - Focus pulses inside the IR without interfering with the accelerator or detector

HEP 2: Polarized Positron Sourcery



- Start with an 2-7 GeV electron linac (dependent on photon choice)
- Collide the electron bunches with a circularly polarized laser pulse to produce high energy photons (60 MeV)
- Convert gammas on W target to obtain the positrons
- Omori proposal gives high demands on electron beam and laser(s)

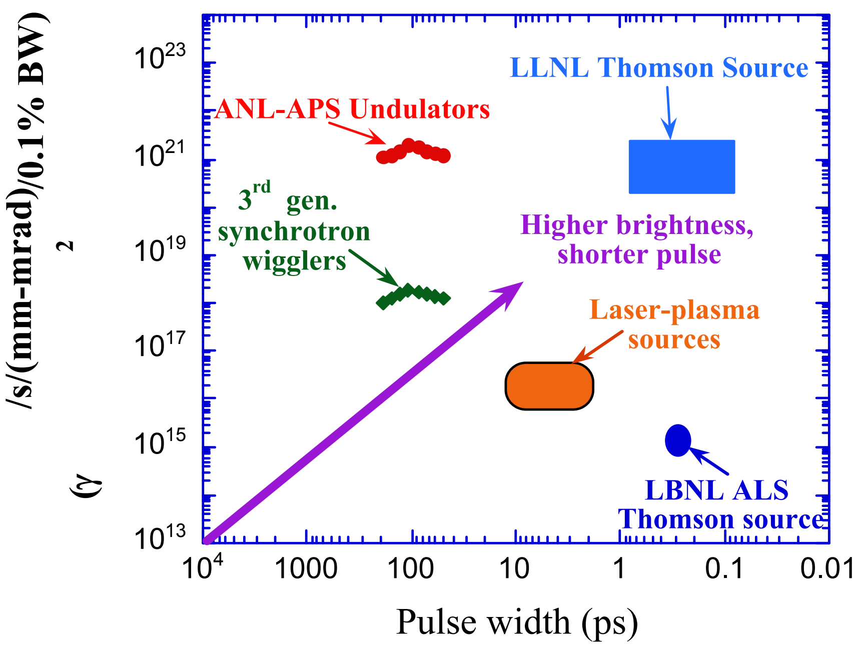
Omori proposal



- -Needs NLC time structure in bunches with very high char (16 nC)
- -Needs **40 lasers**!
- -Lasers are extrapolation of
- -What are these demands compared to state-of-the-art?
- -Can the luminosity be obtain in other ways??
- - Look at UCLA experience?

Present UCLA experience: the PLEIADES source

30 KeV X-ray source capabilities



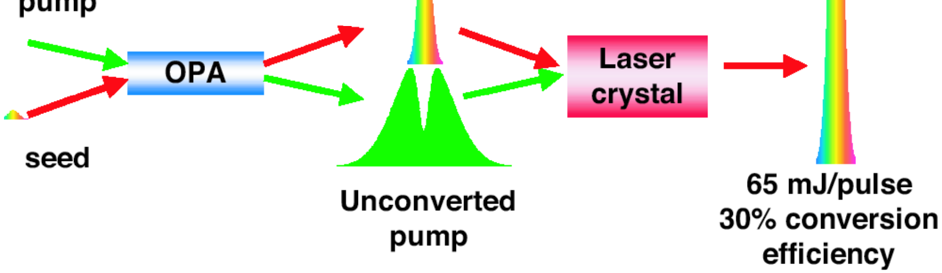
$$\lambda_{sc} = \frac{\lambda_l}{2\gamma^2(1-\beta\cos\psi)}\left[1 + a_l^2 + (\gamma\theta)^2\right]$$

Brightness limited by energy?

- **P**icosecond **L**aser-**E**lectron **I**nter**A**ction for **D**ynamic **E**valuation of **S**tructures
- Joint project between LLNL and UCLA
- High brightness photoinjector linac source
  - 1 nC, 1-10 ps, 35-100 MeV
- **FALCON** laser
  - 10 TW, >50 fs, 800 nm source
- Up to 1E9 x-ray photons per pulse
- Photon energy tunable > 30 kV

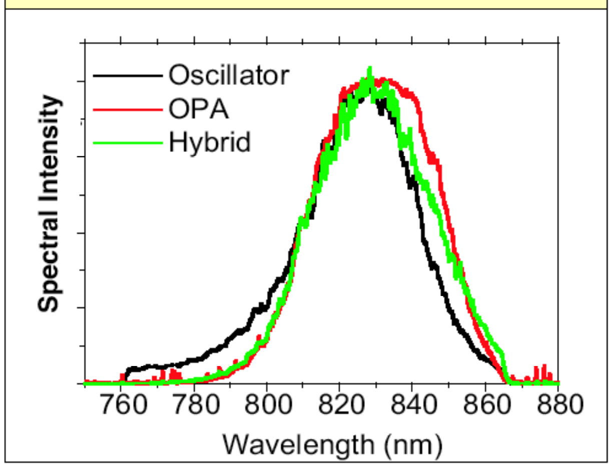
The FALCON laser

OPCPA laser setup

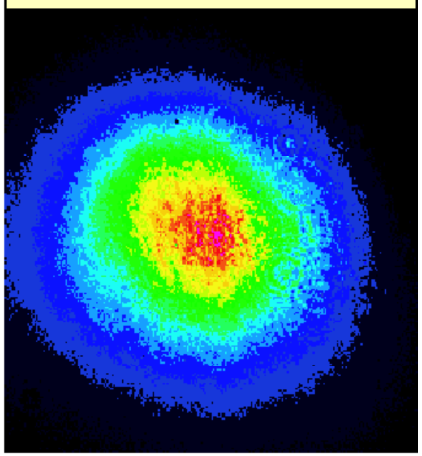


LLNL advanced technology
(not for HEP…)

Broad Bandwidth

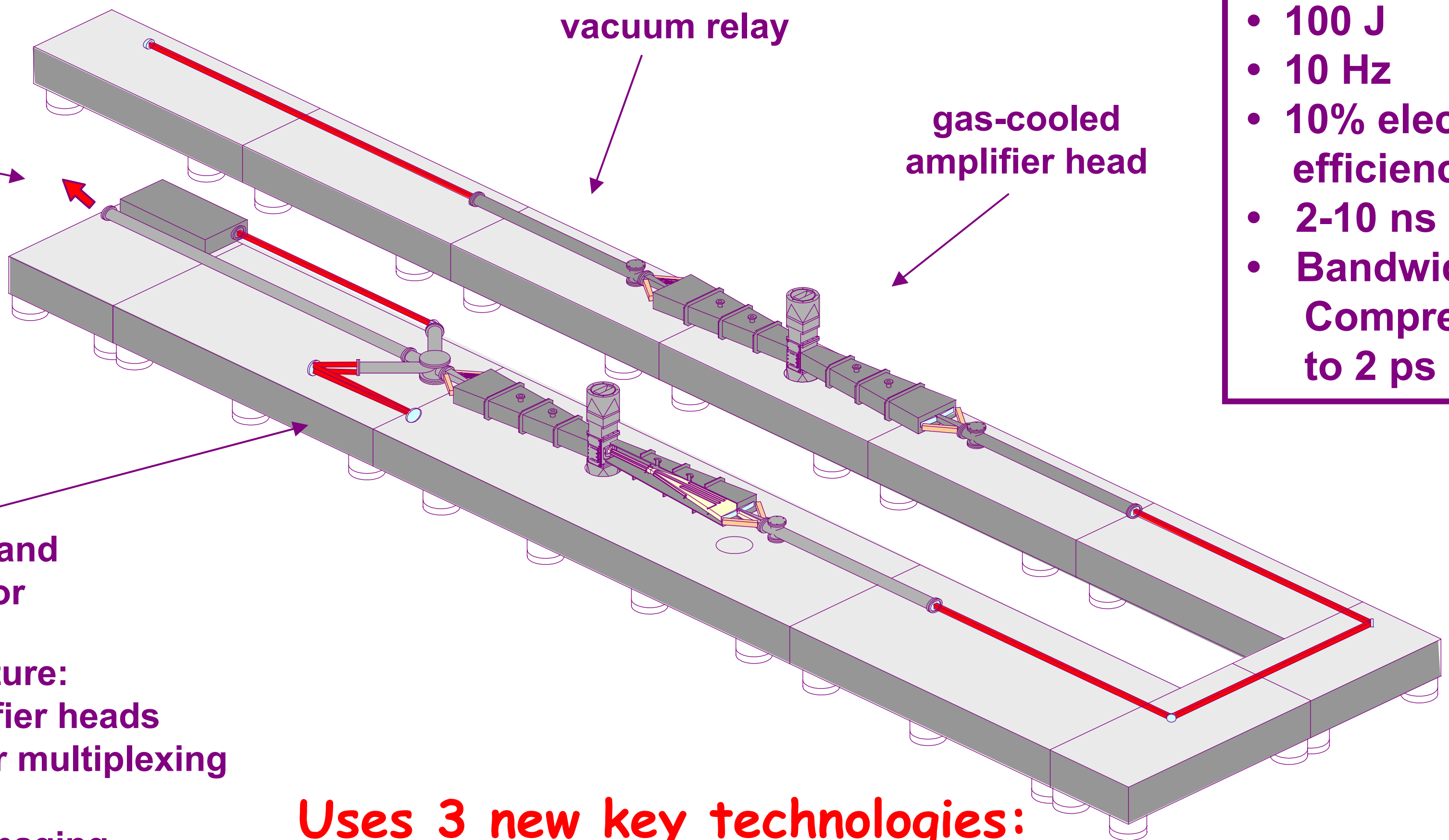


Good Beam Quality



LLNL Mercury laser: Scaling to HEP applications

Goals:
- 100 J
- 10 Hz
- 10% electrical efficiency
- 2-10 ns
- Bandwidth to Compress to 2 ps



Architecture:
- 2 amplifier heads
- angular multiplexing
- 4 pass
- relay imaging
- wavefront correction

Uses 3 new key technologies:
gas cooling, diodes, and Yb:S-FAP crystals

RF Photoinjector

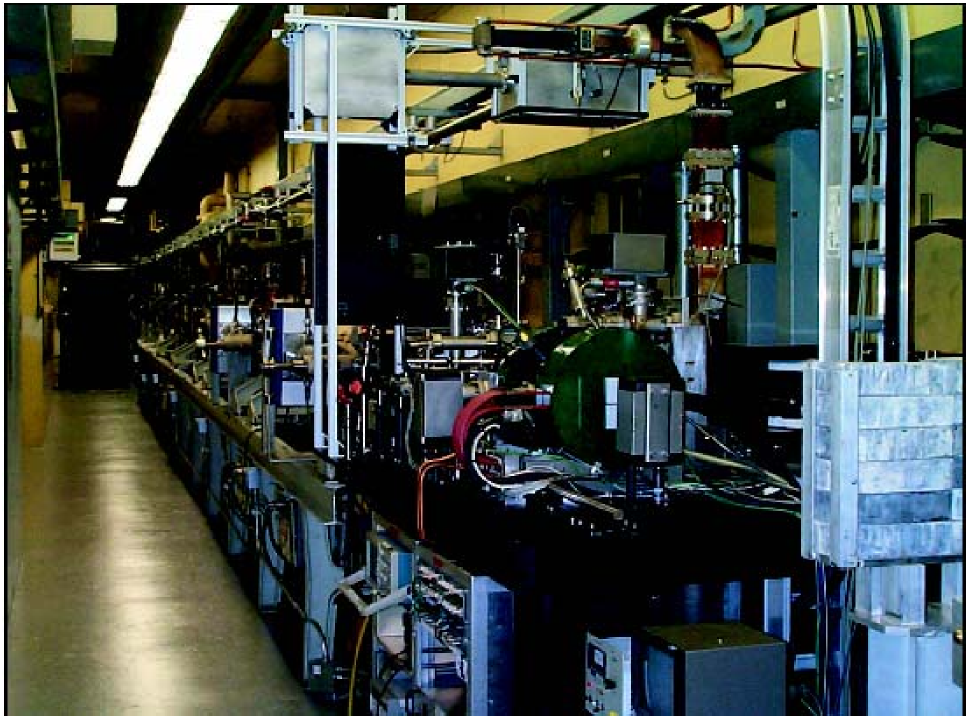
- UCLA responsibility
- 1.6 cell high field S-band (2854.5 MHz)
  - Run up to 5.2 MeV
- All magnets from UCLA
  - Solenoids
  - Bypass quads/dipoles
  - Final focus
    - High field electromagnets
    - PMQ system!
- Use S-band for higher charge…

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.

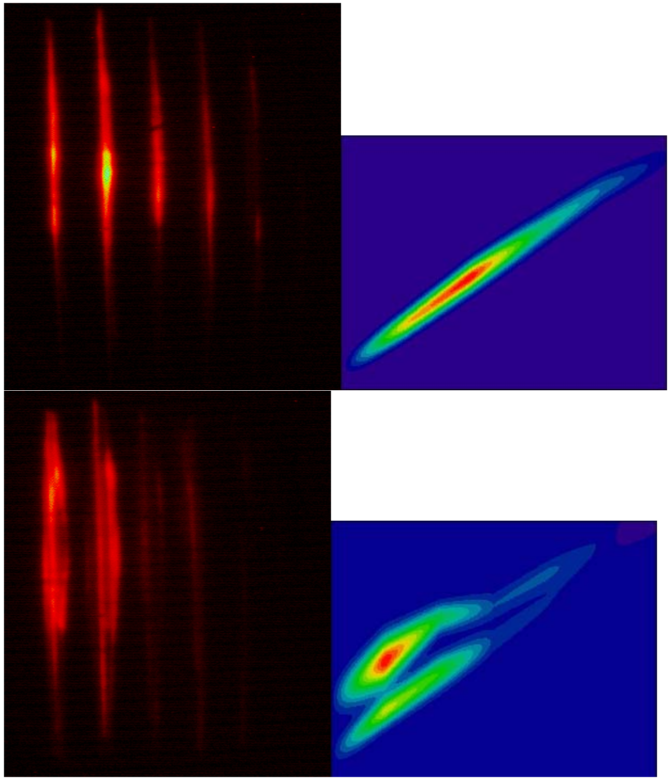
Photoinjector and bypasss

Electron linac

- 35 year old 120 MeV travelling wave linac
- ~~High average current thermionic source for positron production~~
- ~~4 linac sections~~
- Solenoid focusing around each section



Velocity bunching for increased current (Serafini/Ferrario proposal)

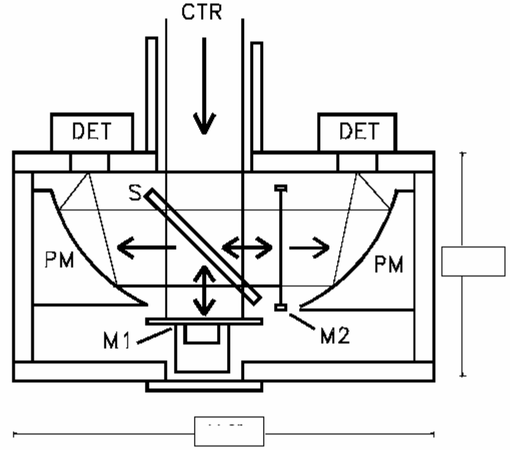


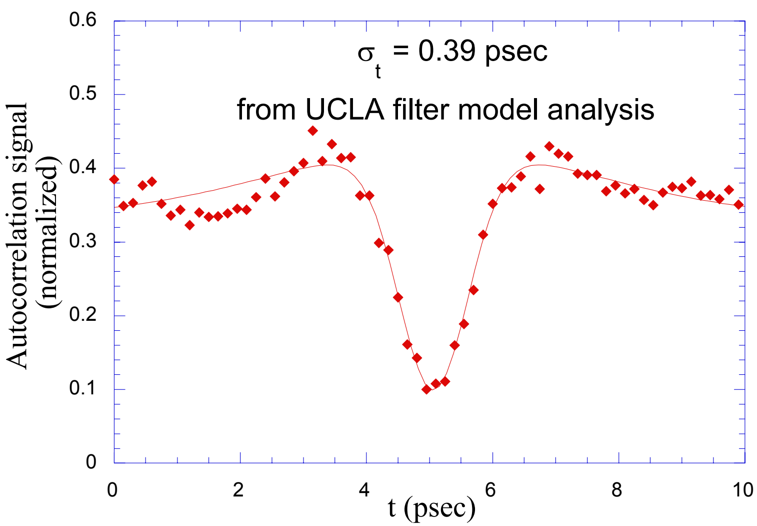
Multi-slit phase space measurement at Neptune showing bifurcation in chicane

- Enhanced photon brightness
- Avoid problems of magnet chicane bunching
- Emittance control *during bunching* using solenoids around linacs
- Bunching effectively at lower energy
  - Lower final energy spread
  - Better final focus…

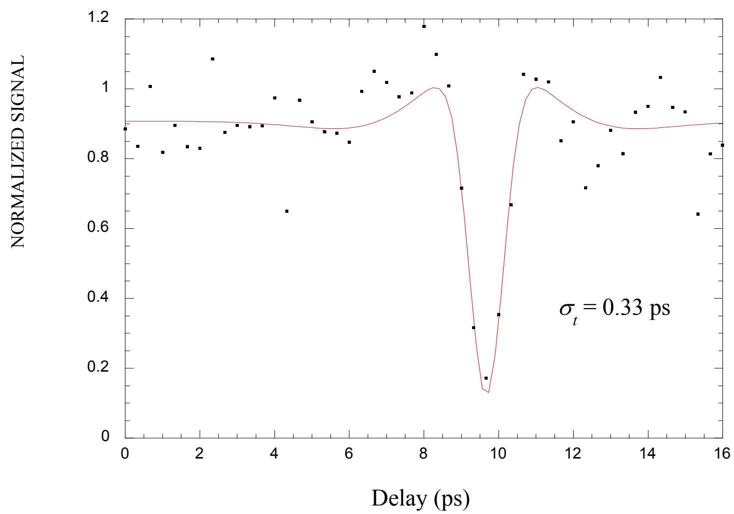
Velocity bunching measurements

- Over factor of 12 bunching shown in CTR measurements
- Better than Neptune "thin-lens" performance
- Next measurements: emittance control



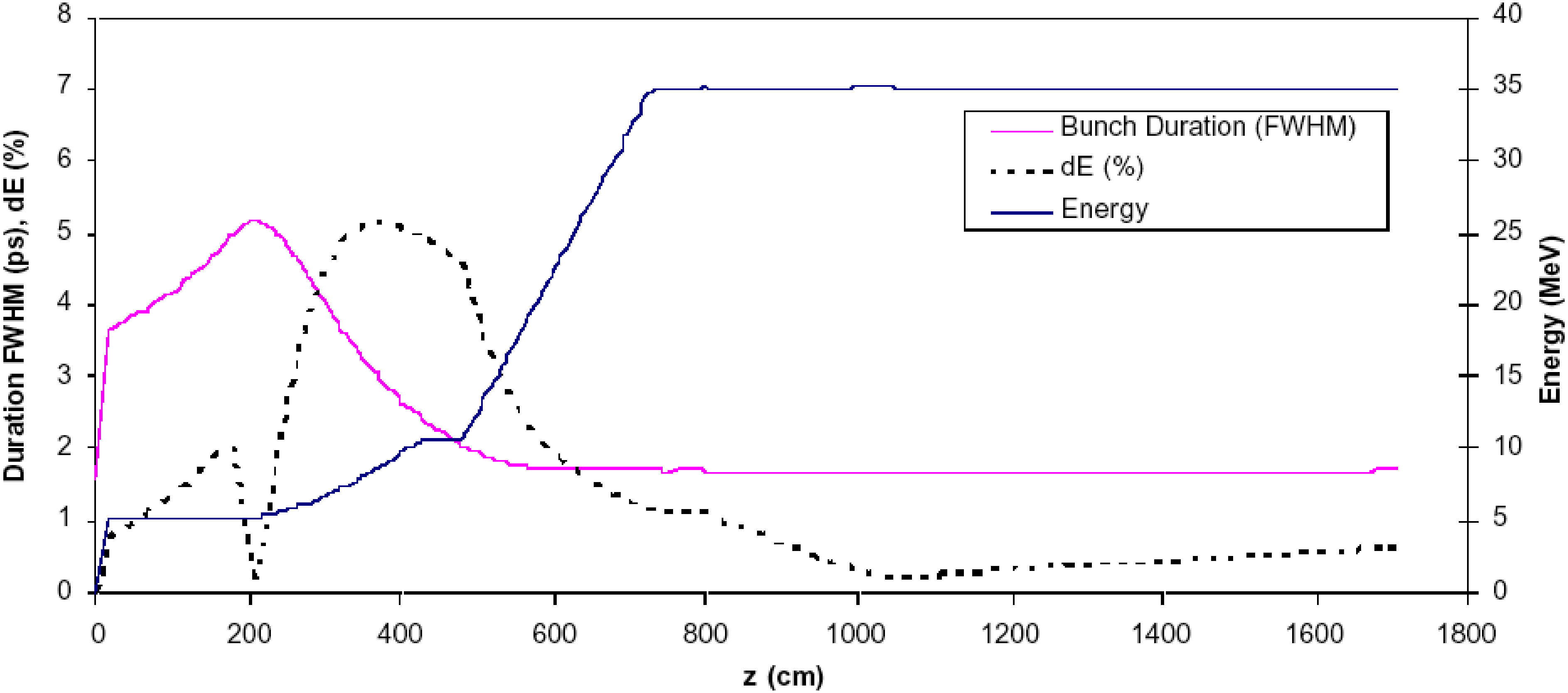


Neptune measurements (PWT "thin lens", no post acceleration)



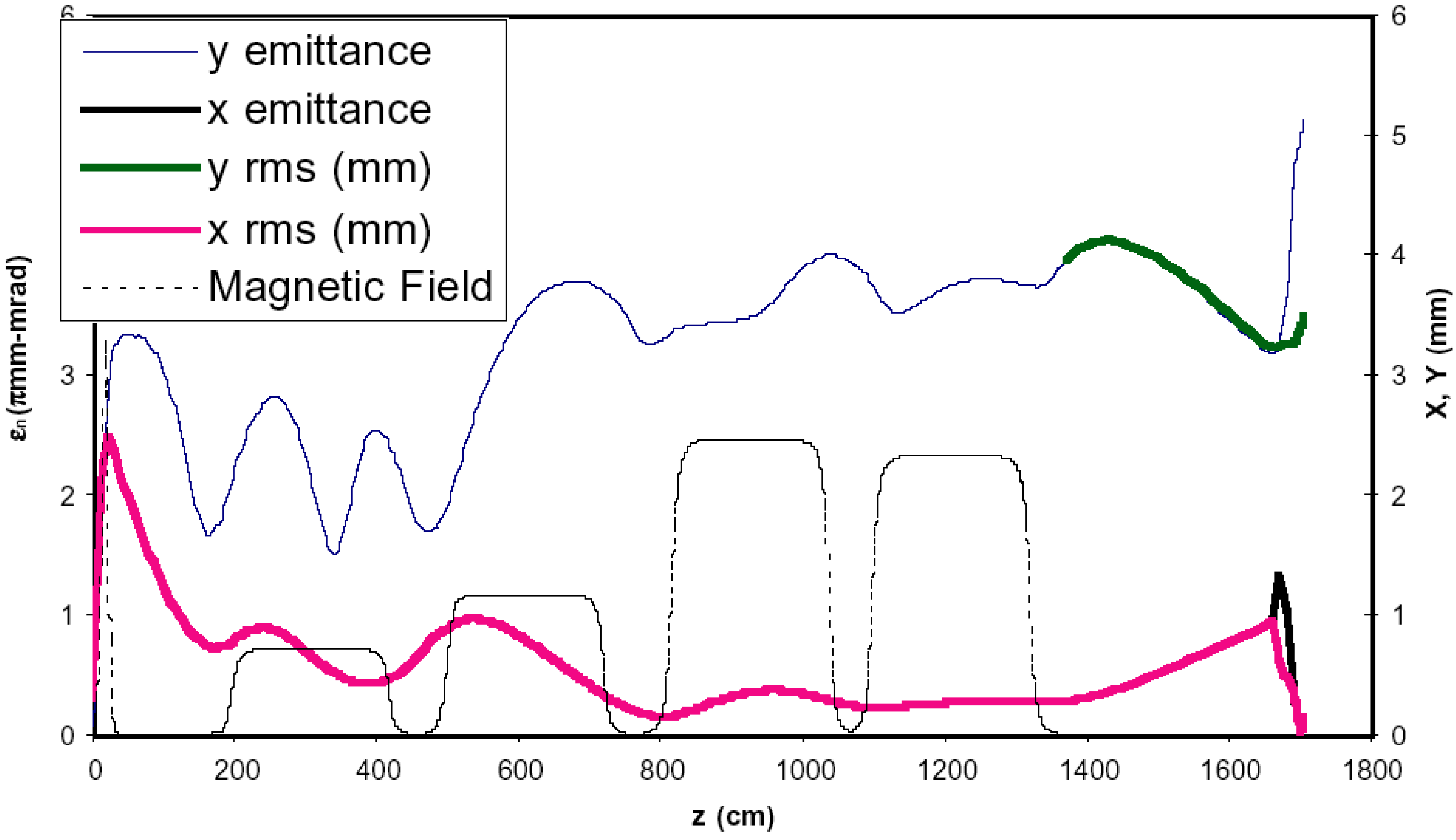
Recent measurement of velocity bunching at LLNL PLEIADES

Start-to-end simulations with final focus: longitudinal dynamics



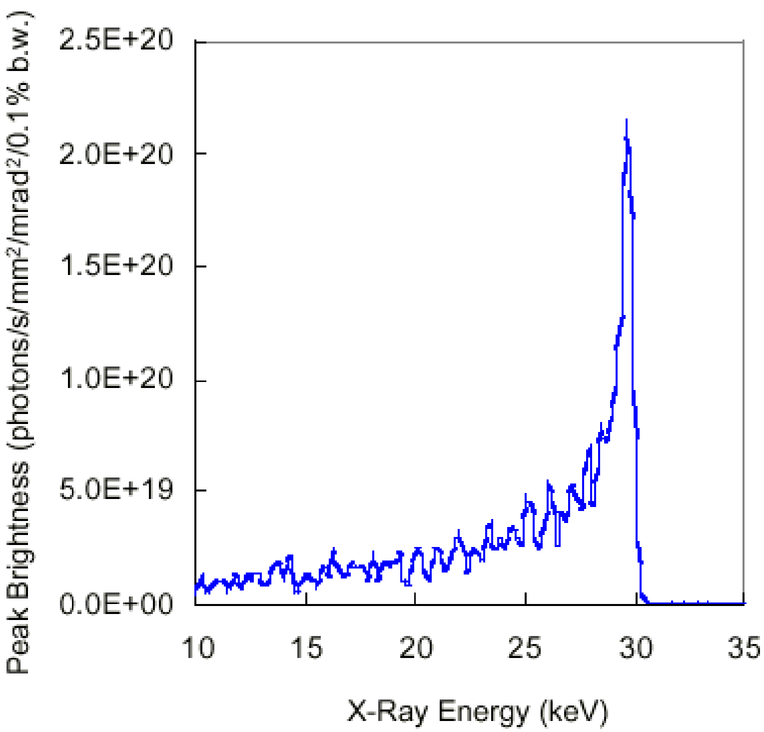
Can/should be repeated for positron source…

RMS beam envelope and emittance control

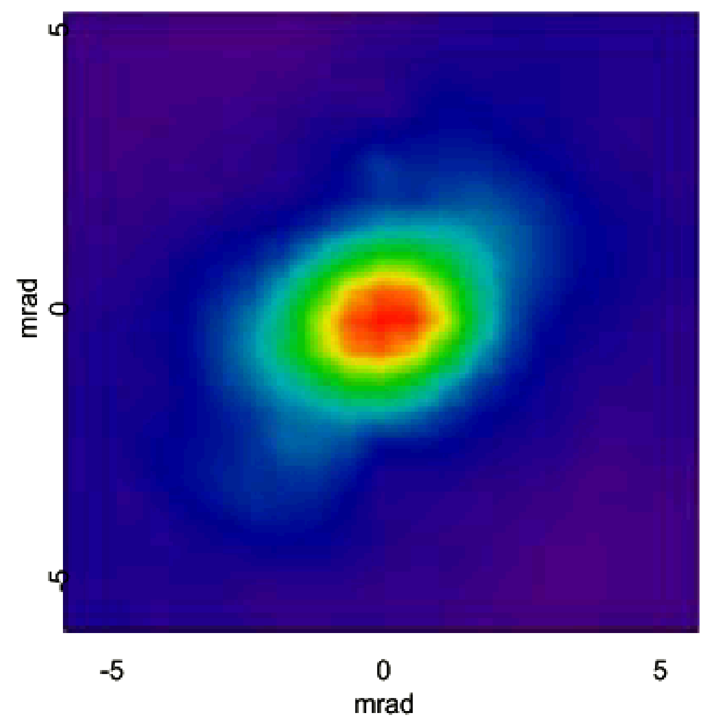


Expectrum

- Linear 3D scattering code (Hartemann)
- Start-to-end with PARMELA…

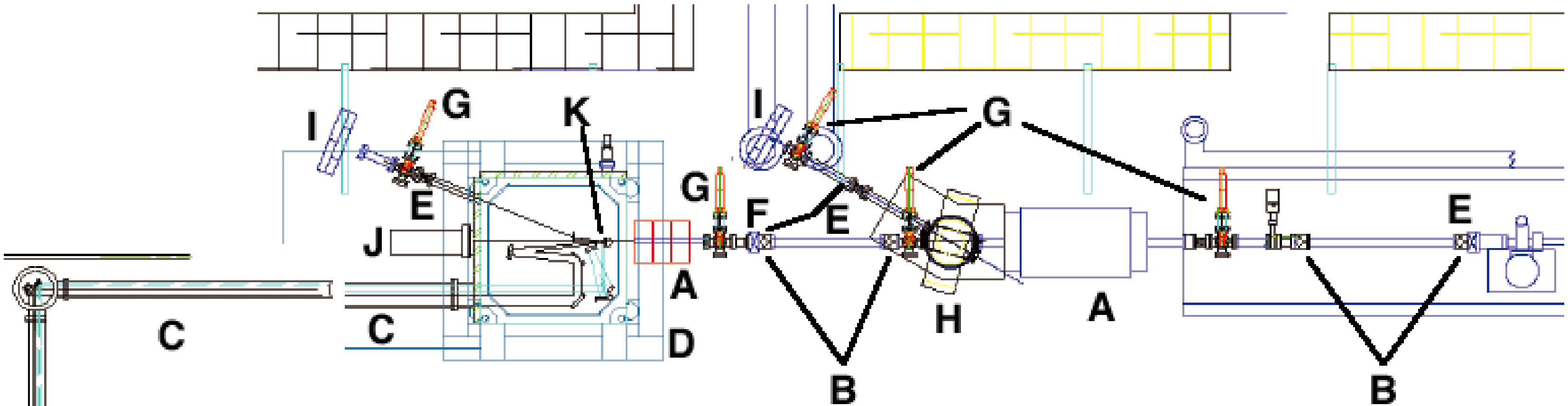


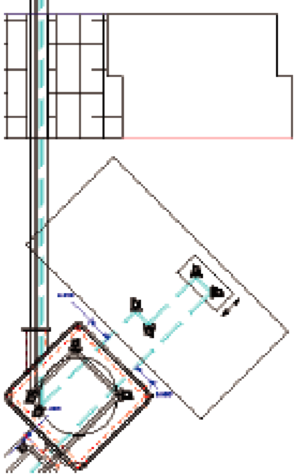
Expected spectrum (angular effects)

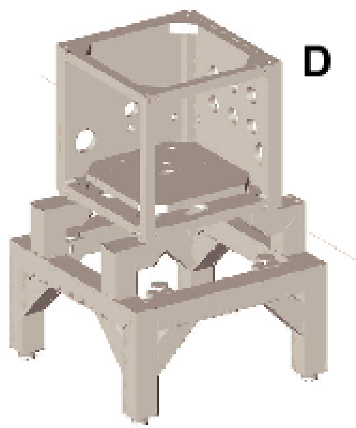


Expected image at CCD (far-field)

Interaction region

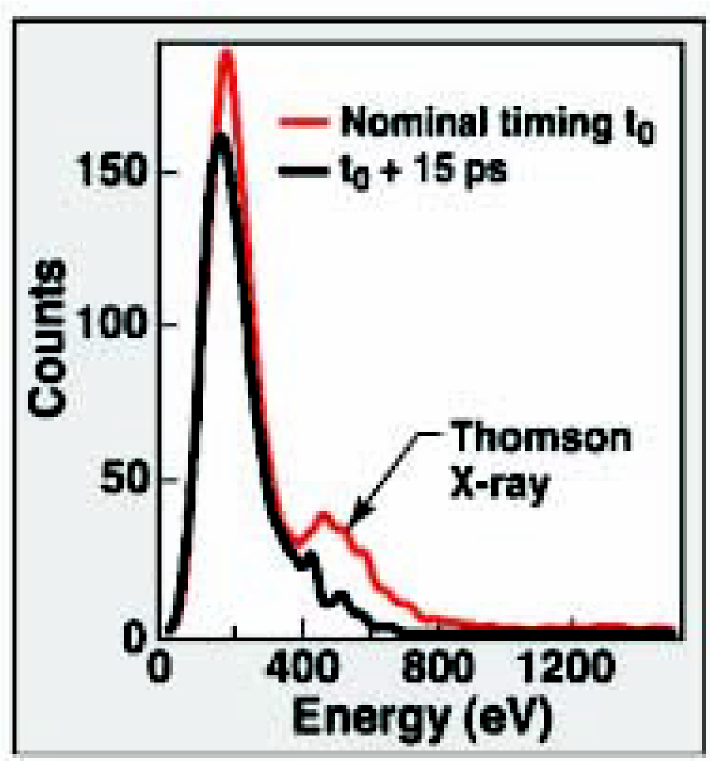






A Focusing Magnets
B Steering Magnets
C Laser Transport
D Interaction Chamber
E Beam Current Monitors
F Beam Position Monitors
G Pop-Ins
H Electric Dipole
I e-Beam Dumps
J X-ray CCD
K OTR foil
L Bend Magnets

First light results



Timing worked out with gun only…

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Masked x-ray CCD image

How do we improve this performance? Final focus…

The problem of the final focus

- Luminosity demands small beams

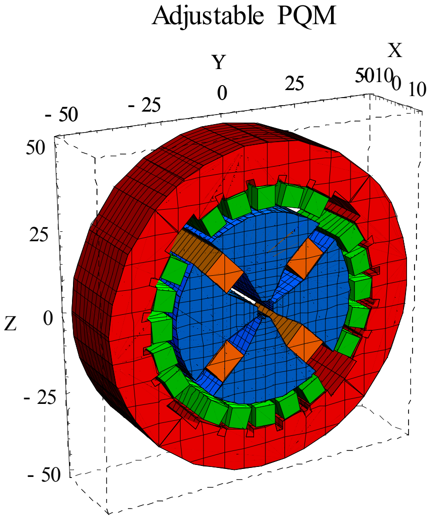
$$N_\gamma = \left[\frac{N_l N_{e-}}{4\pi\sigma_x^2} \right] \sigma_{th}$$

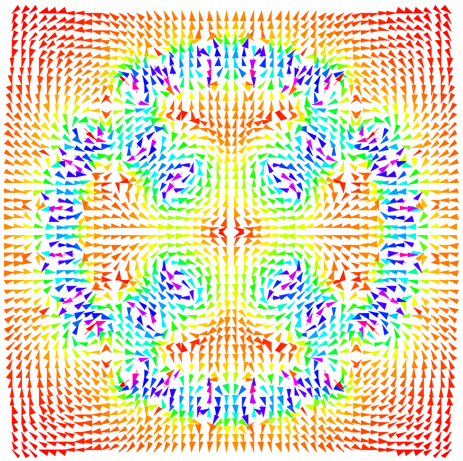
- Compression gives large energy spread
  - Chromatic aberrations
  - Demagnification limit

$$\frac{\sigma^*}{\sigma_0} = \sqrt{\frac{1+\left(\frac{\beta_0}{f}\right)^2\left(\frac{2\sigma_{\delta p}}{p}\right)^2}{\left[1+\left(\frac{\beta_0}{f}\right)^2\right]\left[1+\left(\frac{2\sigma_{\delta p}}{p}\right)^2\right]}} \underset{\left\{\frac{\beta_0}{f} >> \frac{p}{\sigma_{\delta p}}\right\}}{\cong} \frac{2\sigma_{\delta p}}{p}$$

  - Cannot remove chromatic aberrations with sextupoles, etc. Transport too long, costly…
- Quadrupole strength problem
  - Cannot expand beam; space-charge “decompensation” (also with sextupoles)
  - Very attractive option: permanent magnet quadrupoles

Permanent magnet quadrupoles

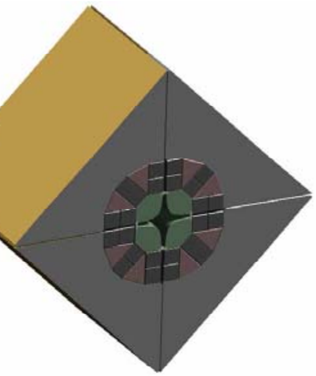


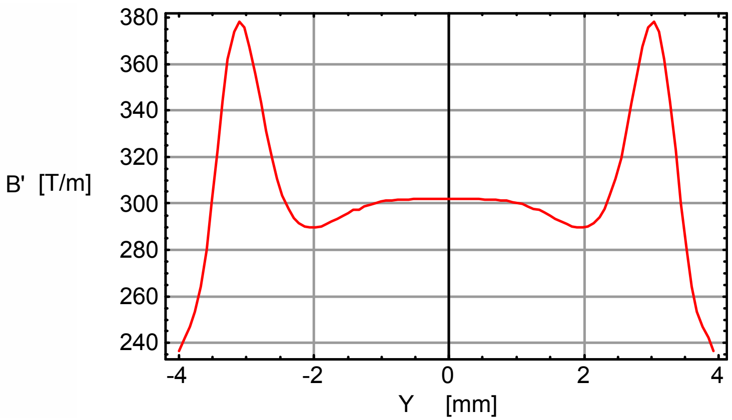


Halbach ring-tuned quad for NLC (UCLA/FNAL/SLAC project), with field map

- PMQs stronger than EMQs
  - >500 T/m v. <25 T/m
- PMQs are quite difficult to tune
  - Need to tune system from 35 to 100 MeV!
  - Tradeoffs between tunability, strength, centerline stability

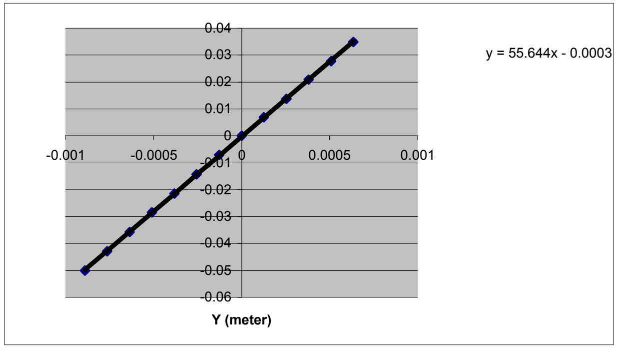
High, fixed field PMQ design?





Moderate field hybrid iron-yoke PMQ design

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

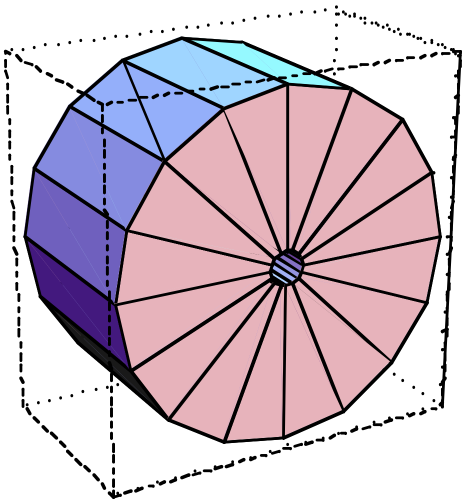


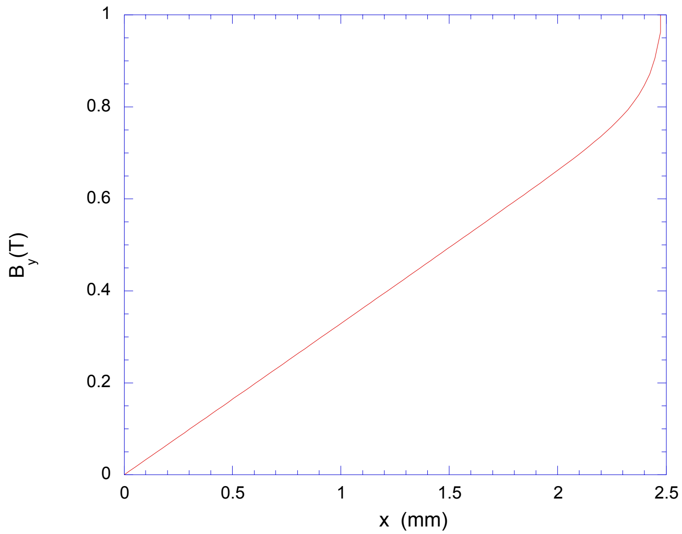
Scaled hybrid PMQ for Neptune

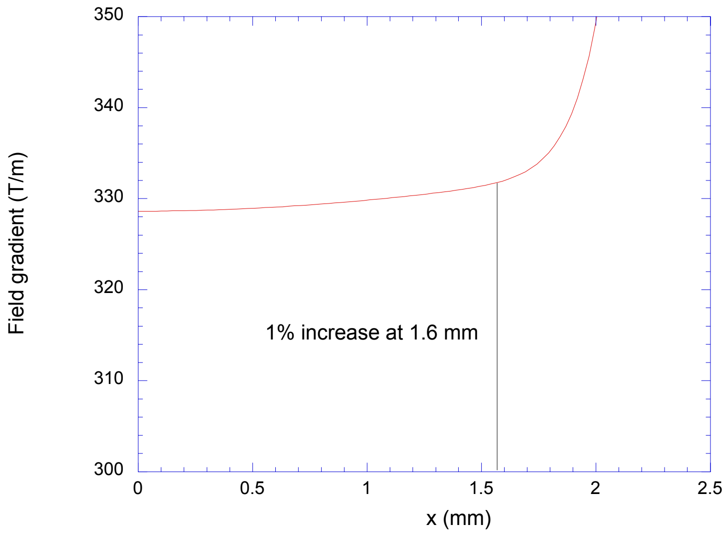
- We decided to *not adjust strength* of PMQs… only *change longitudinal position*
- We have reinvented camera optics…
- Need over 300 T/m for PLEIADES
  - Set by minimum energy of 35 MeV

The Pizza-pie PMQ

- Can obtain >500 T/m with 8 mm ID
- Linearity good over 80% of aperture
- Self/mutual forces small
- Designed at UCLA
- Under construction by industry







Beam dynamics with 5 PMQ configuration (35 MeV)

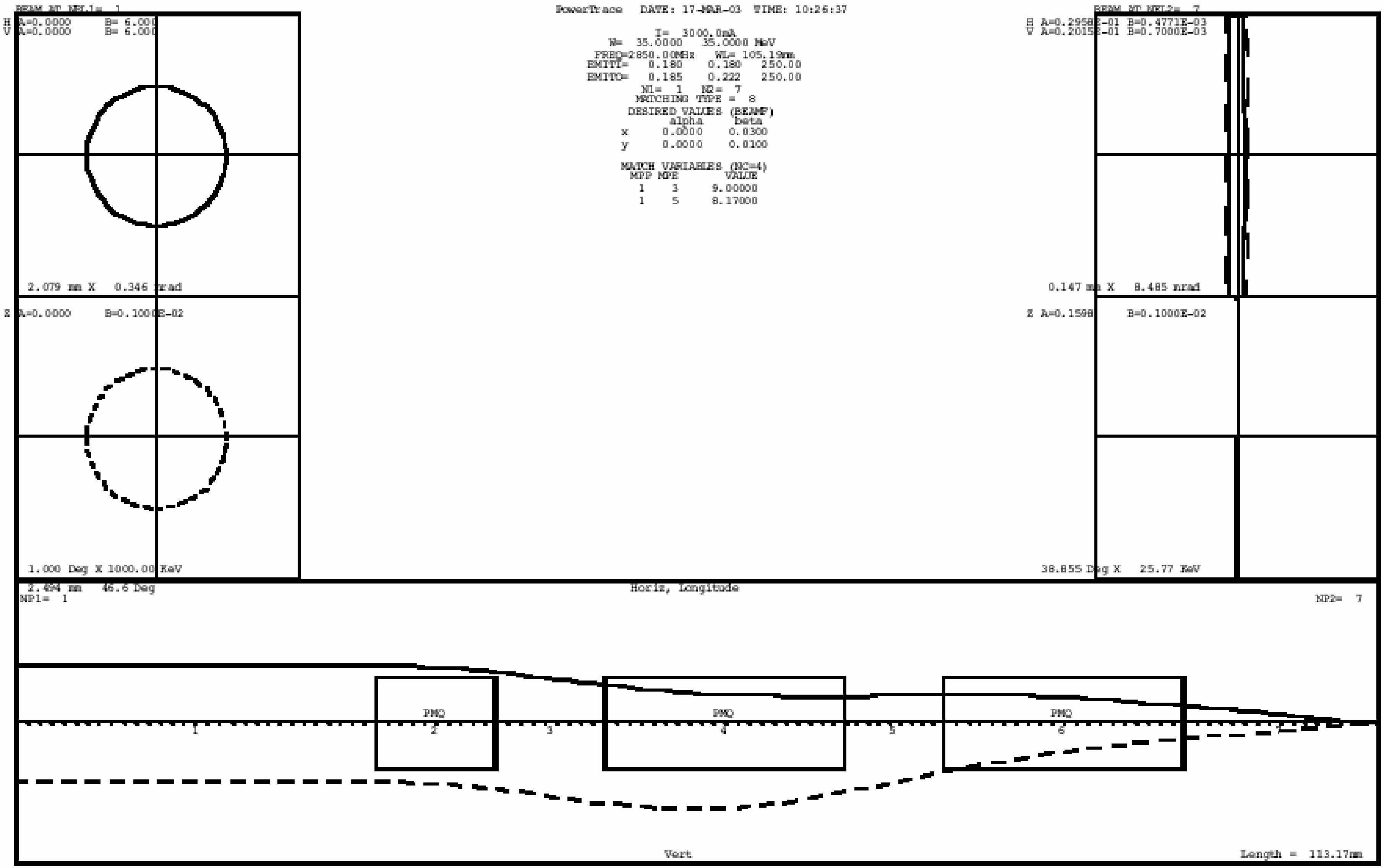
Beta-function ~ 0.7 mm
(not much bigger than σ_z)

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

Beam dynamics with 5 PMQ configuration (50 MeV)

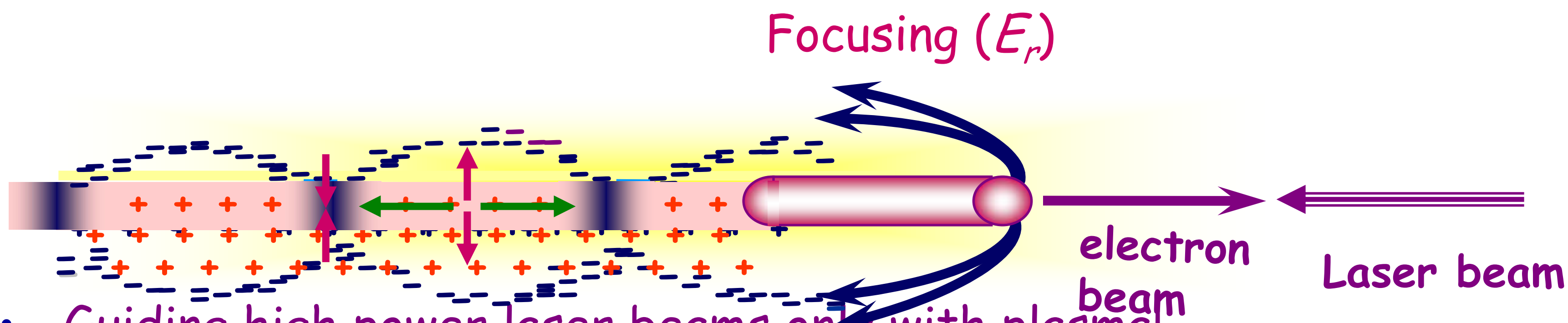
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

Works with only 3 quads… better for moving!



A new direction: PEICS

- Not all sources demand ultra-short time scales. Some need more photons, especially medicine/HEP
- We have gotten small spot sizes; we need to keep them small



- Guiding high power laser beams only with plasma!
- Beam creates own channel; also forms a fiber for the laser: **P**lasma **E**nhanced **I**nverse **C**ompton **S**cattering.
- Use very high charge, long (throw out v-bunching…) electron beam
- Studying the polarized positron source; can we eliminate 39 out of 40 lasers!

Comments on Omori's scheme

- May not be self consistent with diffraction…
- Extra laser focusing does no help much, as the interaction is limited by maximum (polar. loss)

$$a_l = \frac{eE_l}{m_e c \omega_l} < 0.5\,?$$

- Use higher frequency photons? Originally chosen as CO2 to give larger photon population/intensity

$$N_{sc} \propto \left(N_\gamma\right)/\left(\sigma_x^2\right) \propto \left(U_l \lambda_l\right)/\left(\sqrt{U_l}\,\lambda_l/a_l\right)^2 \propto \lambda_l^{-1}$$

- Use more laser energy? Longer laser pulse?
- Use plasma enhancement… only need a factor of 40

Some rules for design

- Make electron beam longer than laser, nearly same as plasma for guiding photons
- Match electron beam (with hot final focus!)

$$\beta = \sqrt{\gamma / 2\pi r_e n_B}$$

- Do not make beam too much denser than plasma (fiber confinement leaves laser beam much larger than e-beam)
- Need e-beam long
- Leave intensity at $k_p \sigma_z >> 1$
- Example at 800 nm (higher laser energy, lower electron beam energy, actively developing laser technology) $a_l < 0.5$

Short wavelength example

# electron	$1\text{x}10^{11}$
Electron energy	1.6 GeV
Norm. rms emittance	10 mm-mrad
Electron pulse length	20 ps (6 mm) (rms)
Matched beta	1 mm
Matched beam size	1.7 microns (rms)
Plasma density	$2\text{x}10^{17}$ cm^{-3}
Ratio of n_b/np	1.8
$k_p\sigma_z$	500
$k_p\sigma_r$	0.2

Photon wavelength	800 nm
Laser energy	1.8 J
Guided spot size	5.2 microns
Rayleigh range Z_r	430 microns
Guiding lengths	14 Z_r
Matched beam size	1.7 microns (rms)
Laser pulse length	5 ps (1.5 mm) (rms)
Laser intensity	$2\text{x}10^{21}$ W/m^2
a_l	0.3
# scattered photons	$5.5\text{x}10^{11}$

Same as Omori

Work to be done…

- Electron beam "format" needs to be studied
  - Charge/single bunch is not problem, pulse train is…
  - Stacking in damping ring?
- Laser has same considerations
  - Mitigation of the pulse format has advantages
- Electron beam/plasma/laser interaction must be studied
  - Underway at UCLA with simulation effort
  - Plasma fiber formation
  - Electromagnetic mode confinement; return currents
  - Electron beam angular effects
  - 10% average energy loss in beam…